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EXPERIMENTAL VLF RELATIVE NAVIGATION
ON R/V ATLANTIS II, CRUISE 15

by

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November 1966

TECHNICAL REPORT

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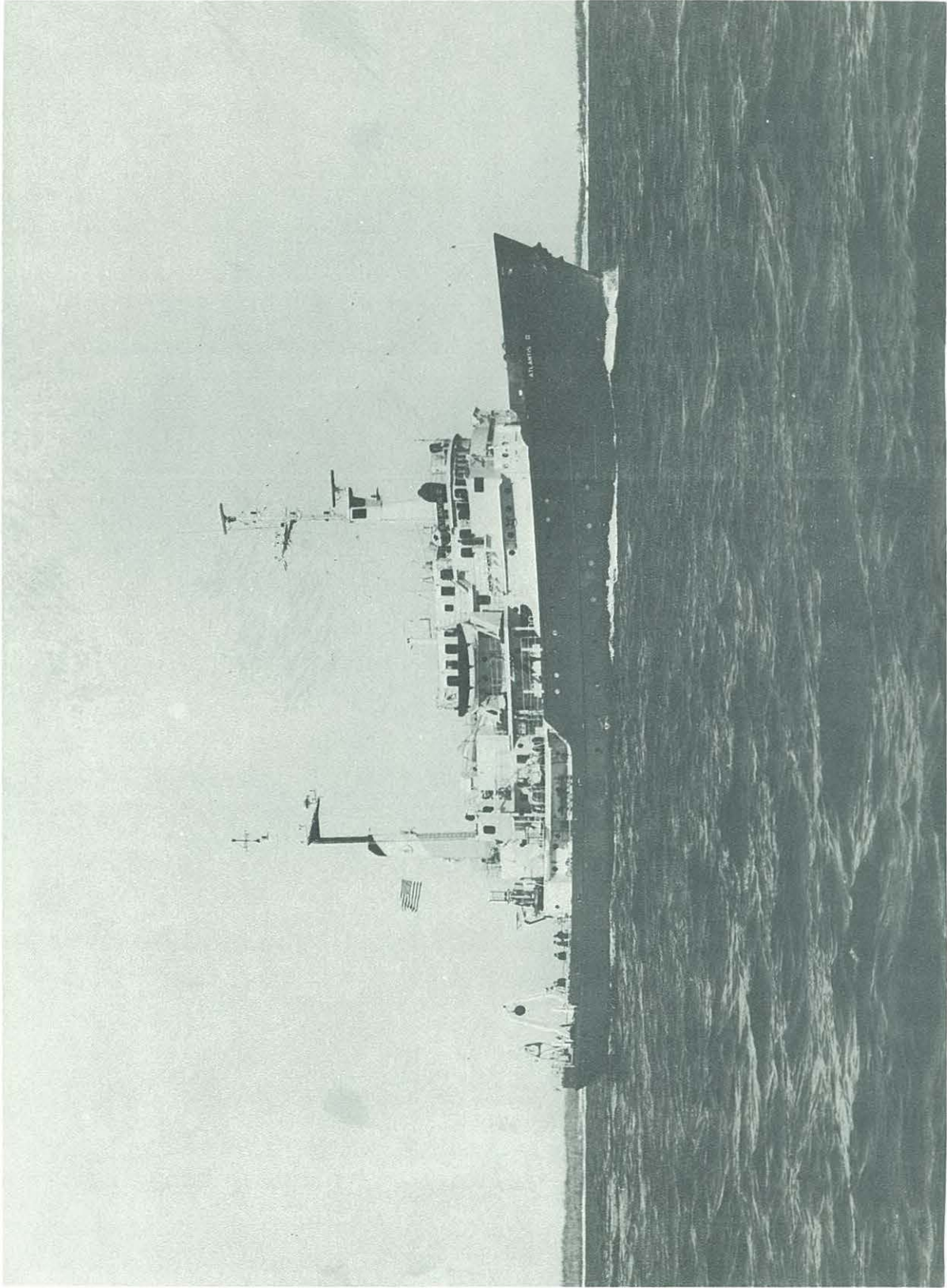
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R/V ATLANTIS II

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ABSTRACT

An experimental long-range relative navigation system was employed on the Research Vessel ATLANTIS II of the Woods Hole Oceanographic Institution during Cruise 8 to the Indian Ocean in 1963 and Cruise 15 which circumnavigated the globe in 1965.

The very low frequencies (VLF) transmitted by stations having stabilized carriers (a few parts in 10^{11}) can be received throughout the world. Navigational information is obtained from the comparison of the received signals of two or more stations with a precision oscillator which serves as a reference. Geographical changes result in phase changes which may be computed to longitude and latitude if the starting point is known; thus, the system is relative.

Reference points could be supplied to the VLF system from a satellite radio navigator that was loaned to the U. S. Navy for this cruise. Best positioning agreed to within three nautical miles from best ship's position under favorable conditions. The VLF equipment also was able to provide (1) a measure of ship's drift on station, (2) precise time and frequencies, and (3) a means for calibrating the ship's EM log at sea.

1. Introduction

If an oceanographer were planning a cruise today to many parts of the world's oceans, he would find that his navigation would depend solely on celestial fixes and occasional land sightings. This situation exists in spite of the many electronic aids to navigation that have been developed and which, for one reason or another, either are not available or have insufficient range. If the oceanographer chooses to improvise, he might well consider VLF relative navigation which is available, relatively inexpensive, adaptable for future Omega operations, and will cover vast areas of the oceans, but not all.

Long-range navigational information is derivable from the frequency stabilized transmissions of very low frequency (VLF) radio stations (Pierce, 1957). The control of their frequencies is usually by the combination of several atomic resonators and crystal oscillators to within a few parts in 10^{11} . By comparing the signals from two or more of these stations received on ship with a high precision oscillator for a reference, a relative navigation system may be obtained. Any geographical change from a known point results in phase changes between the received signals and the reference which can be computed to longitude and latitude. This is a relative system since an initial known point is required (Stanbrough and Keily, 1964; Stanbrough, 1965). If

the known point is time, longitude and latitude are not obtained; but relative movement since the starting time is obtained.

Several oceanographic institutions have conducted experiments using the VLF transmissions with varying results. The major effort since 1963 in the USA and Canada has been by Bedford Institute for Oceanography, the U.S. Naval Oceanographic Office, Scripps Institution of Oceanography and Woods Hole Oceanographic Institution. The Research Vessel CHAIN (WHOI) is now in the eastern Mediterranean with a simplified VLF system and soon will be working the hot brine areas of the Red Sea discovered by R/V ATLANTIS II and DISCOVERY III. In 1963, ATLANTIS II made a cruise to the Indian Ocean with a VLF system which achieved partial success in regions as far as the southeastern Indian Ocean. Only stations GBR, Rugby, England, and NBA, Panama Canal Zone, were suitable for reference because other more distant stations more or less coincided with the GBR great circle path; and with the greater range, there were periodic long path signal interferences (7,000-10,000 nautical miles from ship to stations).

For the world-wide cruise of ATLANTIS II in 1965 (figure 1), an improved VLF relative navigation and timing system was on board; and at the same time, the US Navy provided the loan of the AN/SRN-9 satellite radio navigator with accuracies that have been reported to within tenths of a mile. ATLANTIS II was very fortunate to have such a navigator on the longest cruise ever made by Woods Hole, and it was

RV ATLANTIS
CRUISE 15 Jan. - Nov. 1965

Figure 1 Cruise track of R/V ATLANTIS II, Cruise 15, January to November 1965.

opportune for the author to check on VLF relative navigation and its compatibility with the satellite navigator. One of the great difficulties on previous cruises had been that known points were few and far between in mid-ocean, particularly with overcast skies. Over periods of several weeks, errors caused by lane ambiguities, reference drift, and propagational phenomena would occur. With the satellite navigator, accurate positioning would be possible several times per day and would provide starting and check points for the relative system. At the beginning of the cruise in January 1965, there were three satellites that were operable; by November 1965, there was one.

There are several important factors that must be considered to properly use VLF navigation. These are the degree to which the stations maintain their frequency and station on time, the stability and reliability of the reference oscillator (less than 2×10^{11} is desired), the propagational variations, plotting of the fix, and the stability and reliability of the receiving equipment. These variations limit the precision of positioning by relative techniques from 0.3 to 3.0 nautical miles over the daylight period of one day to several days.

2. VLF Stations

The VLF regions are defined as the range from 3 to 30 kilocycles per second (kcs) (Davies, 1965) and there are seven stations useful for VLF relative navigation operating between 16.0 and 26.1 kcs. These stations are for communication and timing purposes; the Omega

stations are found at 10.2 and 13.6 kcs. The U. S. Navy operates NAA on 17.8 kcs at Cutler, Maine, NBA on 24 kcs at Panama Canal Zone, NPG on 18.6 kcs at Jim Creek, Washington, NPM on 26.1 kcs at Hawaii, and NSS on 21.4 kcs at Annapolis, Md. The US Bureau of Standards operates WWVL on 20 kcs at Ft. Collins, Colorado. Station GBR on 16 kcs at Rugby, England, has been off the air most of 1966 and has been replaced by GBZ on 19.6 kcs. It is expected that GBR will resume transmitting of time signals by late 1966.

Three stations, NSS, NBA and GBR (or GBZ), give good coverage of the North and South Atlantic (figure 2). Other stations, such as NAA, WWVL, NPG and even NPM in Hawaii, can be of use in the Western Atlantic. In figure 3, range circles are drawn for the stations that provide the best coverage of the North Atlantic. VLF relative navigation is a circular grid system and, for best results, it is desired that stations be selected with good intersecting lines, as near 90 degrees as possible.

While the VLF stations try to hold their frequencies to within a few parts in 10^{11} , there are signal deviations that introduce errors. This may be seen in figure 4 of the deviations of GBZ, NSS and NBA from a reference of 300×10^{-11} for the period of 15-29 June 1966 (from Daily Values of Frequencies, published weekly by the U. S. Naval Observatory, Washington, D. C.). A deviation of 10 microseconds is equivalent to 1.62 nautical miles; 6.18 microseconds is equivalent to one nautical mile (this value is not constant over the VLF range but is sufficient for

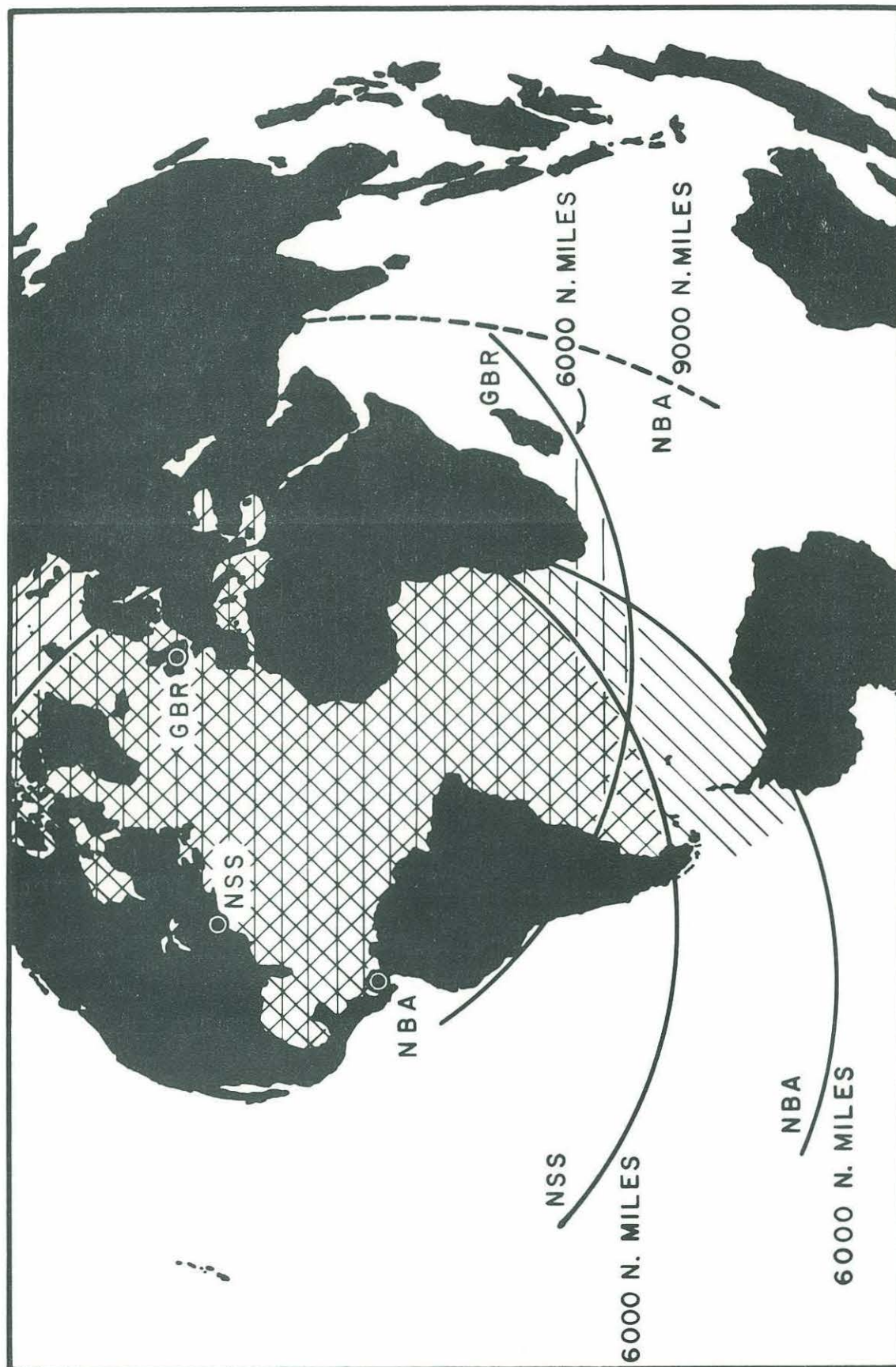


Figure 2 North and South Atlantic coverage by VLF stations NSS, NBA, and GBR.

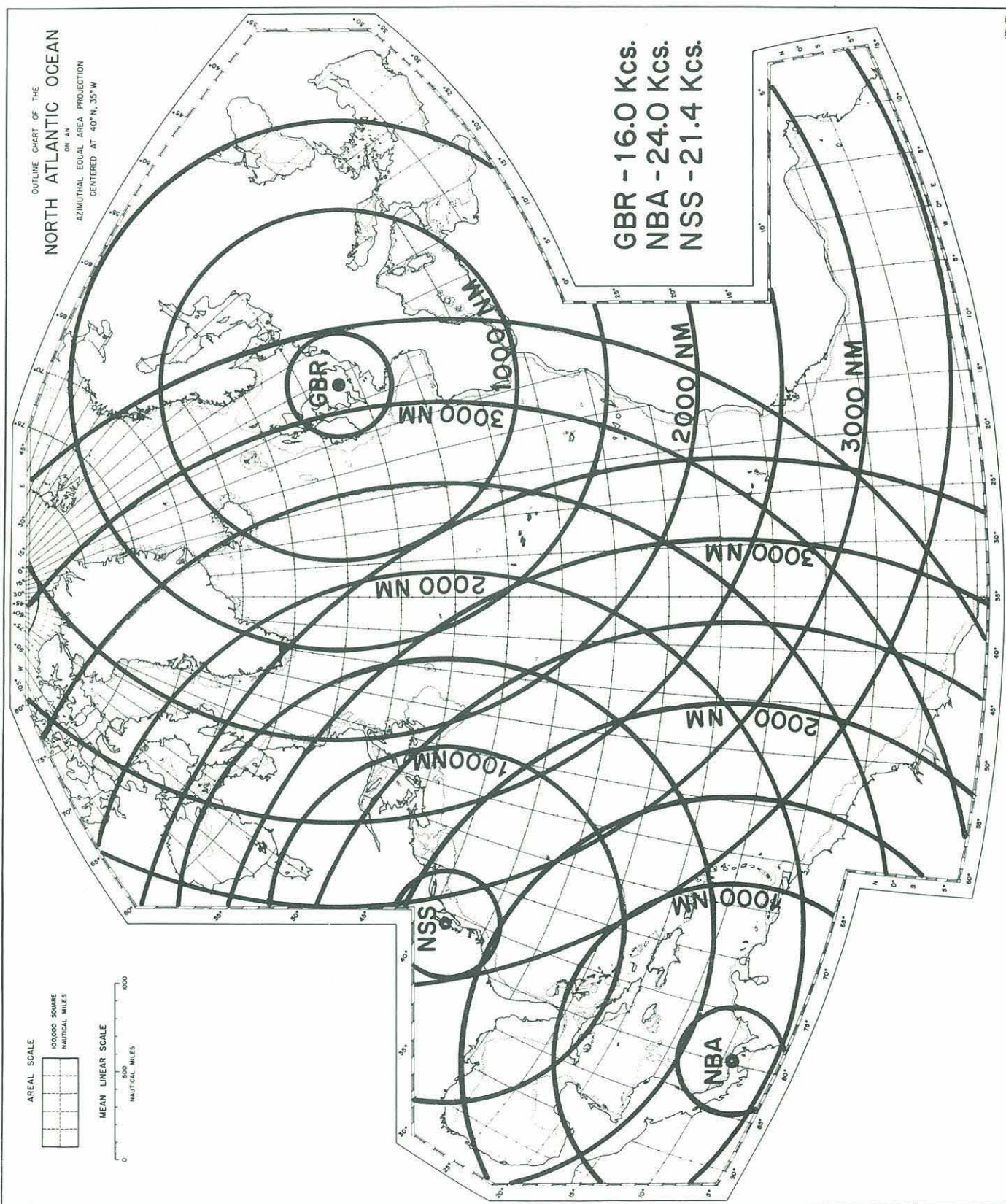


Figure 3 Circular grid coverage of North Atlantic by VLF stations useful for relative navigation.

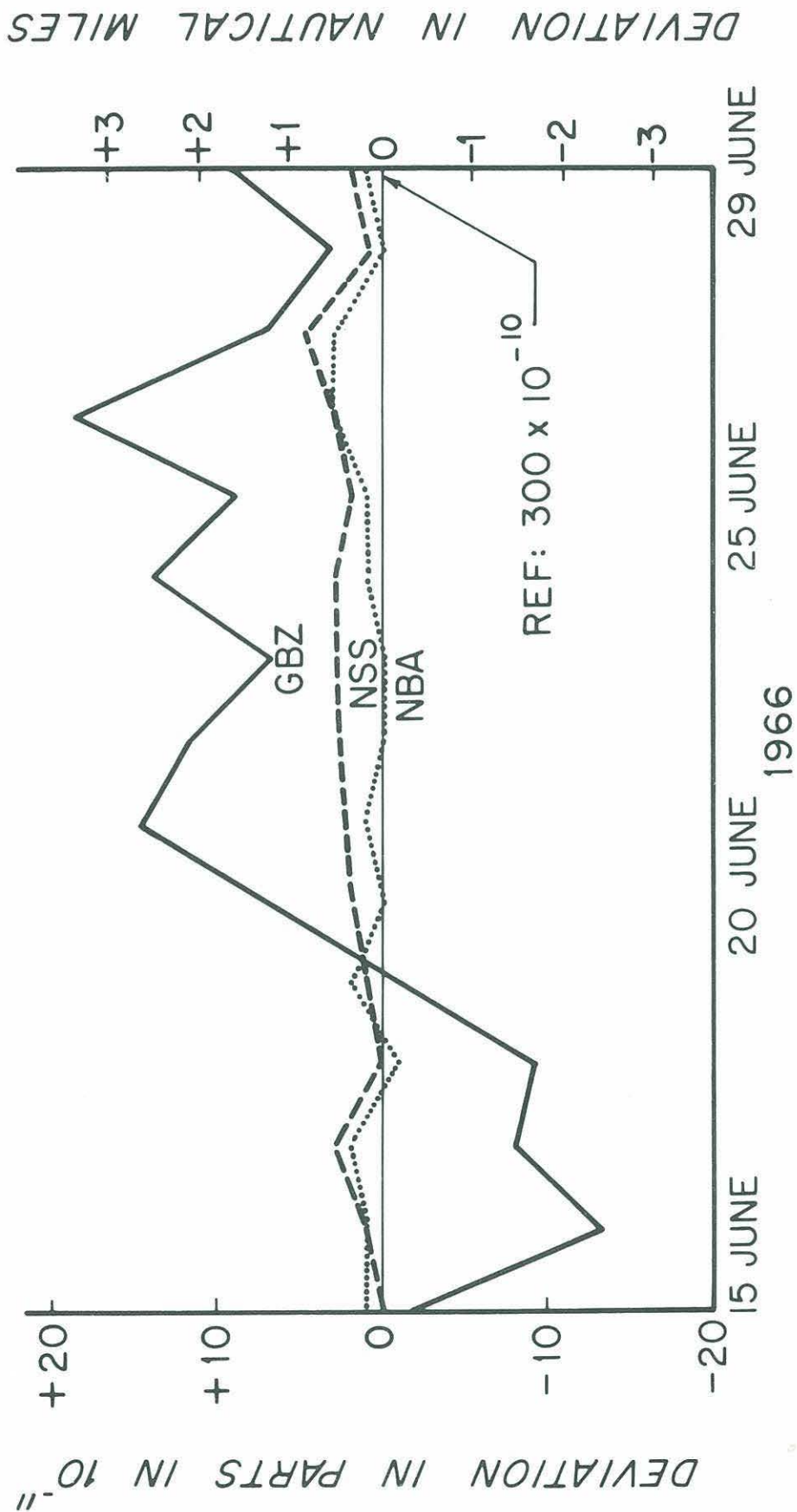


Figure 4 Signal deviations of GBZ, NSS, and NBA and the corresponding errors in nautical miles if used for navigation, 15-29 June 1966.

these considerations). WWVL, while not shown, hold their frequencies to ± 1 microsecond; NSS and NBA deviations are small but still introduce up to a mile error. While GBZ has great excursions shown in this figure, it is expected that GBR will be much superior when transmissions resume.

3. Propagational Effects

Very low frequencies are propagated between the earth's surface and the D layer of the ionosphere as in a wave guide. Many aspects of the propagation of VLF waves to great distances can be explained by wave guide theory (Budden, 1957; Blackband, 1964). Others have contributed to the understanding of phase velocities and propagational phenomena (Casselman, Heritage and Tibbals, 1959; Taylor and Jean, 1961; Lewis and Rasmussen, 1962; Norton, 1960; Wait, 1961-1963). It has been found that the D layer of the ionosphere has a well-defined boundary between 70 kilometers and 90 kilometers according to whether it is day or night. Meteor showers and solar flares (Chilton, Steel and Norton, 1963) may slightly affect the signals. The diurnal phase variations of VLF signals over long paths repeat surprisingly well from day to day and is in the form of a trapezoid when recorded. At the transition time between sunrise and sunset, there is a possibility of slipping a phase (Walker, 1965) under unique conditions. Diurnal effects can be predicted (Westfall, 1961), the transition period can be determined (US Obs. 1962), and phase slippage can be observed and corrected.

The very low frequencies suffer but little attenuation and can be received world-wide. The directional dependencies of propagation are 2 dB/1000 km, west to east, and 3 dB/1000 km, east to west. The one kilowatt signal of WWVL, Fort Collins, Colorado, has been received and tracked by the author in the Mauritius area of the Indian Ocean.

Other factors which may effect propagation are frequency, surface conductivity, ionospheric and magnetic disturbances, ground wave interference and local anomalies.

4. VL F System

The VL F relative navigation and timing system employed on R/V ATLANTIS II, Cruise 15 (figure 5), consisted of three receivers, reference oscillator, digital clock, standby power supplies, and had a precision 60 cps output. In addition, the system operated off a common ship antenna (long wire), had a simulator for station off-air times, and the receiver outputs and ship's course were recorded.

VL F phase tracking receivers, which have been developed in recent years for timing, have the sensitivity and stability to conduct navigational exercises. They should have sensitivities of approximately 0.01 micro-volt at the antenna input to the receiver and tracking errors not more than 0.5 microseconds relative to the received carrier (Baltzer, 1963). It is preferred that the receivers be modular for easy servicing at sea and that blanking circuits should be adequate against transmissions of high power shipboard transmitters and lightning storms. The receiver

VLF RELATIVE NAVIGATION AND TIMING SYSTEM *R V ATLANTIS II, CRUISE 15*

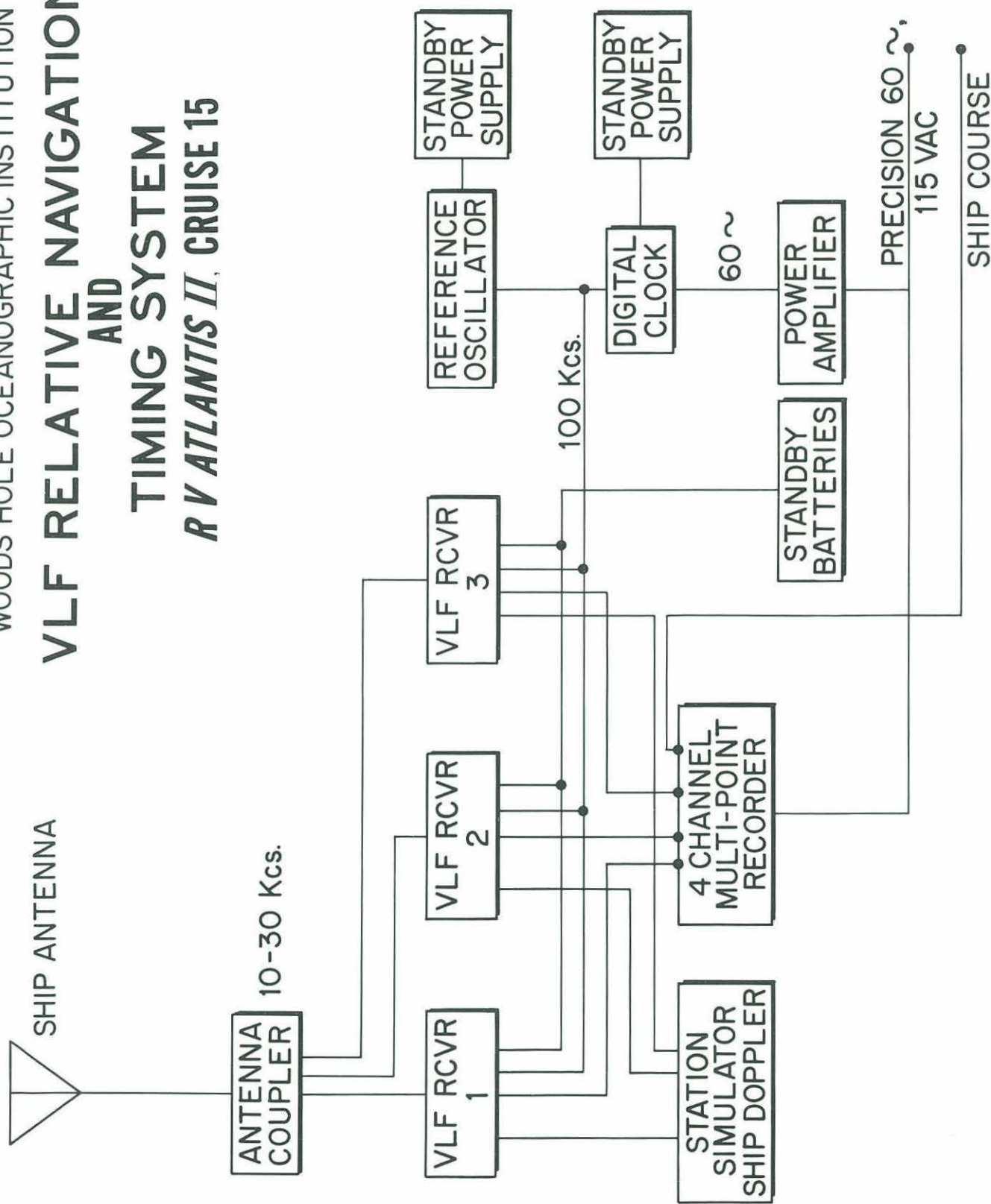


Figure 5 VLF relative navigation and timing system, R/V ATLANTIS II, Cruise 15, January to November 1965.

microsecond tally dials should read to 0.1 microseconds (98.4 ft) and a variable time constant of 5 to 150 seconds is desired.

A Sulzer Model 2.5 oscillator, with nickel cadmium standby batteries, was used on the R/V ATLANTIS II. This oscillator has operated continuously since 1962 and has an aging coefficient of 1.1 in 10^{-11} . At sea, it has been the practice to compensate for this change every other day to hold the oscillator to within 2.5 microseconds (about 1/2 mile maximum error). The success or failure of VLF relative navigation appears to rest here. If the oscillator is not compensated periodically, the frequency offset becomes so great after several days that it is almost impossible to resolve a geographical position (Lear and Swartwood, 1966; Kuehnel, 1964). A rubidium standard, such as the General Technology or Varian, would resolve this problem, but the price is approximately \$10,000 more than three times that of the best crystal oscillator, such as the Sulzer. However, for inexperienced or casual operators, an atomic standard would greatly simplify the task of determining VLF fixes.

The digital clock and precision frequencies obtained with the VLF equipment are by-products that have been extremely valuable. During the entire cruise, the digital clock was constantly used by the ship's officers; and the precision frequency was used for all recorders, the electromagnetic (EM) log for ship's speed, timing for the shipboard computer, and other shipboard clocks.

The recorded output of the receivers and ship's course is shown in figure 6. Time runs from right to left and is marked in hours GMT. Each excursion across the recording is 100 microseconds (16.2 nautical miles). In effect, the phase changes have been changed to time which is equated to miles after plotting. (It has been argued that phase changes referred to as time changes are confusing in describing VLF propagation (Crombie, 1964); however, for navigational purposes it appears more appropriate). Figure 6 also shows that the readings from GBR are diminishing about 60 microseconds per hour, which indicates that the ship is approaching at a vector speed of 10 knots; NBA is increasing by 80 microseconds per hour or about 12 knots. These data are plotted in figure 8. The ship's course is recorded to permit dead reckoning, if needed, when a station goes off the air for a scheduled maintenance.

5. Charts and Computer Computations

One of the great nuisances in the use of VLF relative navigation has been the lack of circular grid charts. For the most part, it has been up to the individual investigator to make his own charts, usually from great circle computations (Westman, 1962). In 1963, the U. S. Naval Oceanographic Office prepared VLF relative navigational charts, VLF 30-67, 68, 81 and 82, of the Western Indian Ocean for the author. Since then, the digital computer at Woods Hole has been utilized to prepare data for chart construction. The arithmetic for a circular grid system is similar to Loran except that the distance between two

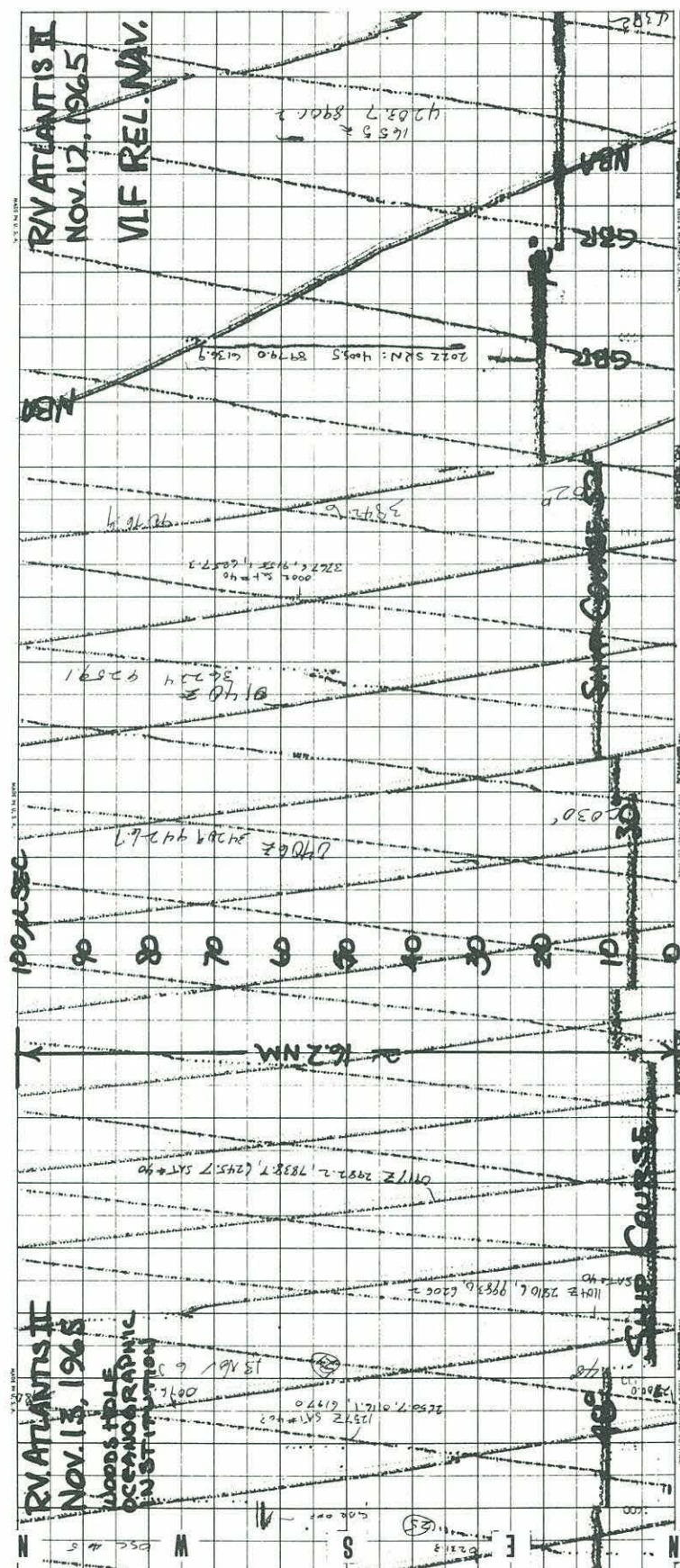


Figure 6 VLF relative navigation recordings used in plotting ship's track.

Loran Stations is set to 0 (Kirkland, 1964). An automatic program has been devised at Woods Hole (Lockwood and Stanbrough, 1966) for determining longitude and latitude points on curves of equal distance from the VLF stations. Elliptical corrections are used. In figure 7 for GBR, a given microsecond range is in the first column and the longitude which has been selected is in column two; the computed latitude is given every 200 microseconds (32.4 nautical miles). Tolerance is 0.05 nautical miles. The program is called automatic in that it is only necessary to change one card in the deck to compute new areas. It is hoped that the computer will be properly programmed soon to plot the points directly to a desired scale. However, hand plotting is not difficult; formerly the plotting of the intersection of range lines and marking time in microseconds was tedious and time consuming.

6. Investigations

About the time R/V ATLANTIS II reached the Indian Ocean in 1965, station NBA went off the air for station overhaul and did not return to operation until October 1965. This was the only station that could give longitude control since the signals from NPM in Hawaii, because of the great distance, were subject to long path interference and were in a day-night path much of the time. It was possible to use the sun lines with the GBR signals to make a crude fix. In the regions to the east of Mauritius in the southern Indian Ocean NPG, Jim Creek, Washington, appeared to have only a slight diurnal effect which gave the appearance of being close to the

STATION GBR		AREA	LAT	15	0.	TO	-5	0.	LONG	40	0.	TO	10	0.	TOLERANCE IS 0.05 NAUTICAL MILES [0.31 USEC]						
USEC	LONGITUDE	LATITUDE	200		400		600		800		000		200		400		600		800		
20000	13	0.	0-49.5	-1	22.5	-1	55.4	-2	28.4	-3	1.3	-3	34.2	-4	7.1	-4	40.0	-5	13.0		
14000	12	30.0	15 36.5	15	3.3	14	30.2	13	57.1	13	23.9	12	50.8	12	17.7	11	44.6	11	11.5	10	38.5
16000	12	30.0	10 5.4	9	32.3	8	59.3	8	26.3	7	53.2	7	20.2	6	47.2	6	14.2	5	41.3	5	8.2
18000	12	30.0	4 35.5	4	2.5	3	29.3	2	56.4	2	23.4	1	50.5	1	17.5	0	44.6	0	11.7	0	21.5
20000	12	30.0	0-54.2	-1	27.1	-2	0.	-2	32.9	-3	5.8	-3	38.7	-4	11.6	-4	44.5	-5	17.4		
14000	12	0.	15 30.6	14	57.7	14	24.6	13	51.5	13	18.4	12	45.4	12	12.3	11	39.3	11	6.2	10	33.2
16000	12	0.	10 0.2	9	27.2	8	54.2	8	21.2	7	48.2	7	15.2	6	42.3	6	9.3	5	36.4	5	3.4
18000	12	0.	4 30.5	3	57.6	3	24.6	2	51.7	2	18.8	1	45.9	1	13.0	0	40.0	0	7.2	0	25.7
20000	12	0.	0-58.6	-1	31.5	-2	4.4	-2	37.5	-3	10.1	-3	43.0	-4	15.8	-4	48.7	-5	21.6		
14000	11	30.0	15 25.4	14	52.3	14	19.3	13	46.2	13	13.2	12	40.2	12	7.2	11	34.2	11	1.2	10	28.2
16000	11	30.0	9 55.5	9	22.3	8	49.3	8	16.4	7	43.4	7	10.5	6	37.6	6	4.7	5	31.7	4	58.8
18000	11	30.0	4 25.9	3	53.0	3	20.2	2	47.2	2	14.3	1	41.5	1	8.6	0	35.7	0	2.8	0	30.0
20000	11	30.0	-1 2.9	-1	35.7	-2	8.5	-2	41.4	-3	14.2	-3	47.1	-4	19.9	-4	52.7	-5	25.6		
14000	11	0.	15 20.2	14	47.2	14	14.2	13	41.2	13	8.2	12	35.3	12	2.3	11	29.3	10	56.5	10	23.5
16000	11	0.	9 50.5	9	17.6	8	44.7	8	11.8	7	38.9	7	6.0	6	33.1	6	0.2	5	27.3	4	54.4
18000	11	0.	4 21.6	3	46.7	3	15.8	2	43.0	2	10.1	1	37.3	1	4.4	0	31.6	0	-1.2	0	34.1
20000	11	0.	-1 6.9	-1	39.7	-2	12.5	-2	45.4	-3	18.2	-3	51.0	-4	23.8	-4	56.6	-5	29.4		
14000	10	30.0	15 15.5	14	42.5	14	9.3	13	36.4	13	3.5	12	30.6	11	57.7	11	24.7	10	51.8	10	18.9
16000	10	30.0	9 46.0	9	15.2	8	40.5	8	7.4	7	34.5	7	1.6	6	28.8	5	56.0	5	23.1	4	50.3
18000	10	30.0	4 17.4	3	44.6	3	11.8	2	38.9	2	6.1	1	33.3	1	0.5	0	27.7	0	-5.1	0	37.9
20000	10	30.0	-1 10.7	-1	45.5	-2	16.5	-2	49.1	-3	21.9	-3	54.7	-4	27.5	-5	0.2				
14000	10	0.	15 10.6	14	37.7	14	4.8	13	31.9	12	59.0	12	26.1	11	53.3	11	20.4	10	47.5	10	14.7
16000	10	0.	9 41.8	9	9.0	8	36.1	8	3.3	7	30.4	6	57.6	6	24.8	5	52.0	5	19.2	4	46.3
18000	10	0.	4 15.5	3	40.7	3	7.9	2	55.2	2	2.3	1	29.5	0	56.8	0	24.0	0	-8.8	0	-41.6
20000	10	0.	-1 14.4	-1	47.1	-2	19.9	-2	52.7	-3	25.4	-3	58.2	-4	31.0	-5	3.7				

LONGITUDES AND LATITUDES FOR GIVEN RANGES IN μ SECS FROM STATION GBR, RUGBY, ENGLAND.

WOODS HOLE, MASS.

Figure 7 Computed travel times in microseconds and corresponding longitudes and latitudes for construction of navigational charts.

station (possibly because of the nearness to the anti-pode). The author departed from the cruise in Durban, South Africa, and no further measurements were made until Professor C. E. Menneken of the U. S. Naval Postgraduate School joined the ship and operated the equipment from Australia to Japan. He noticed that NPM reception experienced sudden unexplained drops in amplitude. Later, in Hawaii, he was able to compare records with the station and found that there was a correlation to high winds (private communication).

The author rejoined the R/V ATLANTIS II at Panama with Mr. M. J. Tucker of National Institute of Oceanography, England, in November 1965. Figure 8 shows the cruise track plotted from 11-13 November. A satellite fix was taken as a reference and the data recorded in figure 6 were used to plot the VLF fixes. Hourly Loran A fixes were made. For the purposes of this cruise track, the Satellite and Loran positions were considered the actual cruise track and no assessment was made between the two. VLF positions generally agreed in this portion from 0 to 3 miles. Diurnal corrections were made to VLF readings before plotting; a correction of -2.2 microseconds/1000 microseconds travel time to stations was applied to all-night path signals (13.5 microseconds for each 1000 nautical miles), except for NBA at 24 kcs. This value for diurnal effect has been determined from long distance, east to west, and west to east measurements of VLF signals made over the past three years by the author. (See Appendix for additional information).

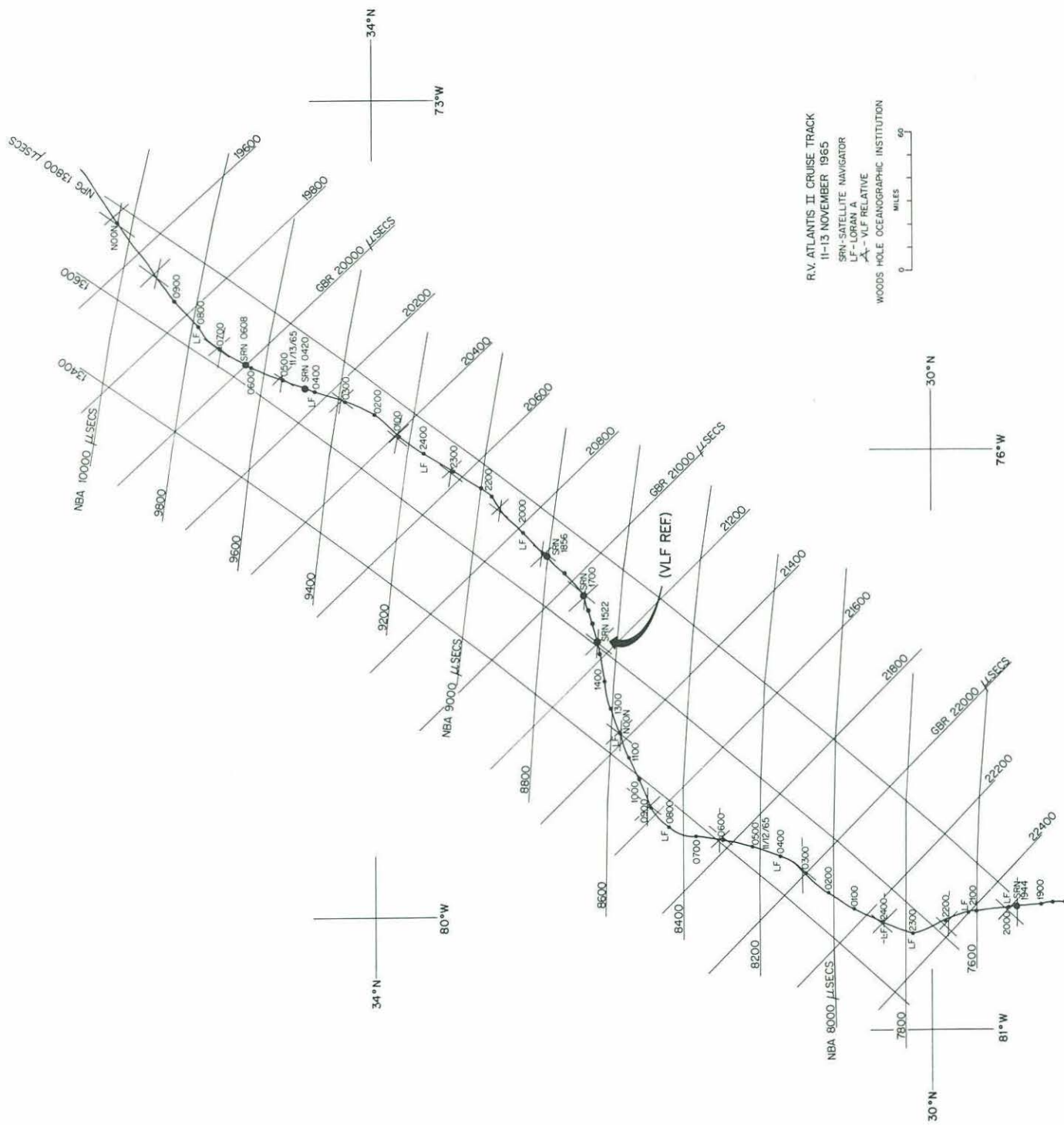


Figure 8 R/V ATLANTIS II cruise track 11-13 November 1965 with satellite radio navigation, Loran A, and VLF positions.

The equipment used in these investigations is shown in figure 9 and is the center rack. The digital clock is at the top and the oscillator is just below. The output of the three VLF receivers is recorded on the Leeds and Northrup recorder. Antenna couplers and doppler simulators are at the bottom of the photograph.

During part of the cruise in the Indian Ocean, the EM log required calibration, and it was possible to use GBR for the measured nautical miles. The ship headed on the bearing vector to the station (during all day path period) for several hours. Microsecond dial readings were noted to the tenths ($98.4 \text{ ft} \approx 0.1/\text{usec}$). Short-term readings were considered as well as five minute averages. There should be little or no surface current since speed over the ground is being determined. A counter run of the ship over the course is desired.

7. Future Developments

It would appear that VLF relative navigation will not be needed once satellite radio navigation is obtained, especially if the price can be lowered to an equivalent cost. However, this is not the case. The accuracy of the satellite navigator has some dependence upon ship's speed. A mistake of one knot in assessing ship's ground speed induces an error of up to 0.25 nautical miles. This is because a minimum of three periods of two minutes for each doppler measurement is made and must be corrected to a point. Ship's heading is necessary. Referring to figure 8, the times of the satellite's fixes, November 12-13, 1965, are slightly less than two hours for several passes then a gap of five

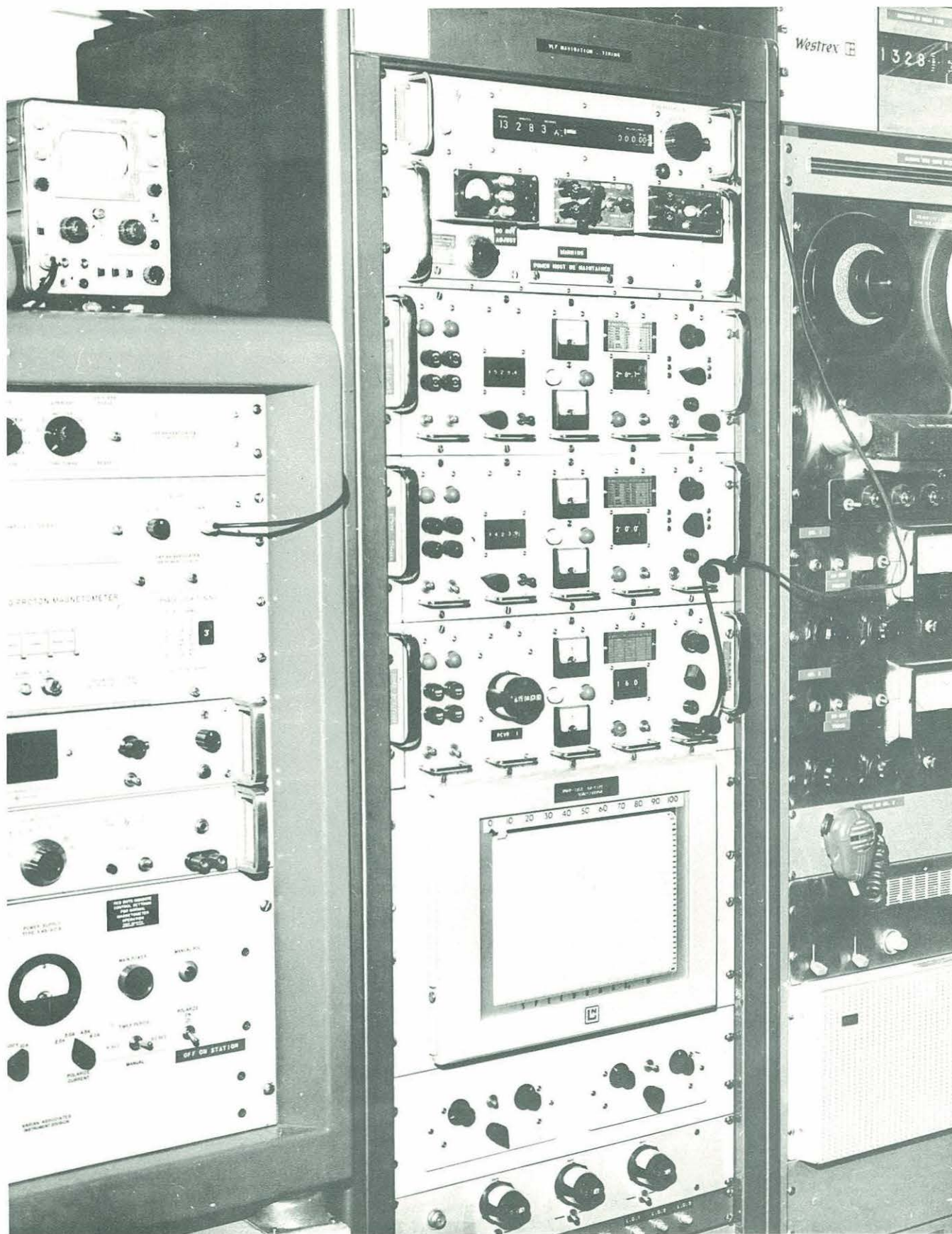


Figure 9 VLF navigation and timing system on R/V ATLANTIS II, Cruise 15.

hours or so occurs. VLF relative navigation can fill this gap.

On-station drift measurements can be made assuredly during all daylight paths, if the distances to the stations are less than six thousand nautical miles, and proper angles of intersections are obtained. With care and at closer ranges the system errors can be kept to less than 0.3 microseconds per hour (equivalent to approximately 0.05 knots). In the North Atlantic at reasonable ranges and during the mid-portion of day path signals, better results may be achieved.

A simplified two-receiver VLF system with an X-Y recorder has been obtained to plot station against station rather than against time; and direct plots of movement on-station will be made. The received signal from one station is applied directly to one axis of the recorder, and this axis becomes the true bearing to the station (and is labeled as such on the plotting sheet). The received signal from the second station connects to the other axis of the recorder; it is attenuated to correspond to the cosine of the angle in degrees between the two stations. Any small portion of the circular grid system may be considered straight-lined without serious errors at long ranges from the stations. The VLF receiver outputs permit a section 16.2 nautical miles by 16.2 nautical miles to be plotted directly before a retrace is made. It is necessary that the inputs to the X-Y recorder be reversible to accommodate stations in various quadrants.

8 Conclusion

Under favorable conditions, VLF transmissions can provide navigational fixes to within one mile and should be most valuable for making ship drift measurements. VLF stations and precision oscillators have been greatly improved in the past three years. The combination of a satellite navigator with VLF relative navigation is attractive for providing precision navigation during the period between passes. The ability to provide precise timing and frequencies for other shipboard uses is a useful by-product. It is also possible to obtain Omega navigation with the VLF equipment described in this report by obtaining a commutator which is commercially available. This would permit the selection of Omega, Omega relative, or VLF relative navigation.

The U. S. Naval Observatory recently released information that minimum shift keying (MSK) would be commenced by several VLF stations over the next few years. A slight modification may have to be made to present-day VLF receivers to track the signals for navigational purposes.

Acknowledgments

The experimental work on R/V ATLANTIS II and the cruise was supported by the National Science Foundation, Earth Sciences Division. The VLF equipment and computer use was supported by the Geophysics Branch of the Office of Naval Research, Contract Nonr-3351.

Appendix

A NOTE ON DIURNAL CORRECTIONS FOR VLF RELATIVE NAVIGATION

The VLF signals are propagated over great distances as in a wave guide between the surface of the earth and the lower part of the ionosphere, the D layer. The apparent height of the wave guide is about 90 kilometers during the night but at sunrise the layer lowers to a height of approximately 70 kilometers due to ionization by the sunlight. Effectively, the walls of the wave guide are brought closer together; and the phase velocity of the signal in the wave guide is increased.

It is worthwhile to apply diurnal corrections to the received VLF signals to reduce the navigational errors in the VLF relative system. For example, refer to figure A-1. The GBR signal received at Zanzibar undergoes a phase change (indicated by the VLF receivers in microseconds) of 60 microseconds (usecs). Assuming that the VLF signals travel one nautical mile in 6.18 usecs, an error of approximately ten nautical miles would be introduced to the nighttime positioning if the reference position was made during a period of all day-path reception. Figure A-2 illustrates the need for diurnal corrections in the Seychelles.

Corrections may be applied by various methods. These are:

- (1) Observing the diurnal patterns over several days while in port in an area of interest, an averaged correction is made for a twenty-four hour period.
- (2) The time of sunrises and sunsets is determined for the stations and areas of interest (from the American Ephemeris and Nautical Almanac). Then the transition period for the change from day to night and night to day is noted; i. e., the number of hours for the change. Next, approximately 13.5 usecs per thousand nautical miles is subtracted from the nighttime readings to equate to day-path readings.
- (3) The diurnal shift may be computed from the knowledge of the earth's rotation, latitude, and longitude of stations and area of interest, etc. Dr. J. A. Pierce, of Harvard University, has derived expressions for the diurnal changes.

A combination of (1) and (2) above was used on the ATLANTIS II cruises in 1963 and 1965. In 1964, Dr. Carl Bowin, of Woods Hole, on a cruise of R. V. CHAIN, introduced the Pierce equations into the shipboard computer and corrections were supplied in real time.

In preparation for the Indian Ocean cruise in 1963, Tables I and II were constructed, having the geographical coordinates of the VLF stations and ports in the desired areas, the distance separating them, the time zones, and the time of sunrises

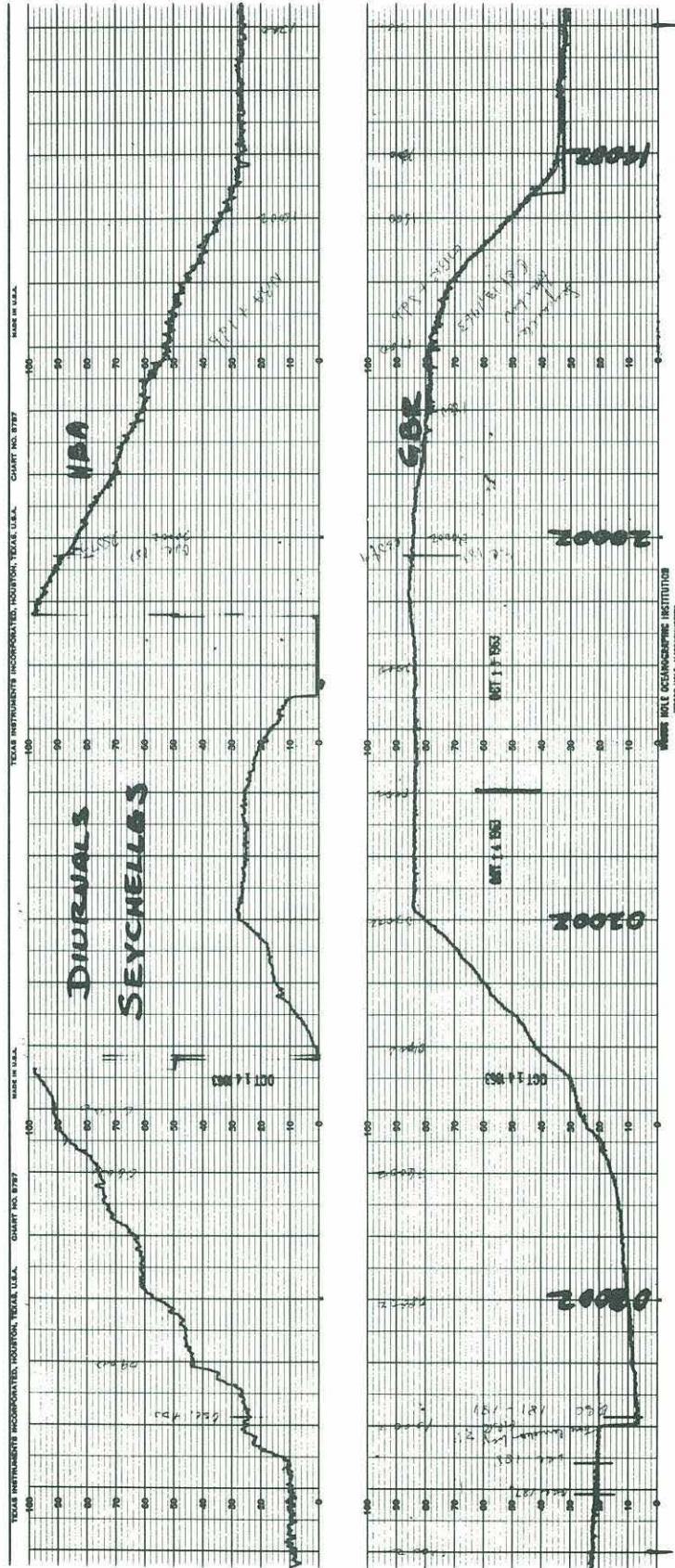


Figure A2 Diurnal patterns of NBA, Balboa, C.Z., and GBR, Rugby, England recorded October 13-14, 1963 at Port Victoria, Mahe, Seychelles.

Ports Stations	ADEN	BOMBAY	COLOMBO	ZANZIBAR	MAHÉ SEYCHELLES	PORT LOUIS MAURITIUS	LOURENÇO MARQUES
	12°47'N 44°58'E	18°56'N 72°50'E	6°57'N 79°51'E	6°10'S 39°11'E	4°37'S 55°27'E	20°10'S 57°50'E	25°58'S 32°35'E
GBR 52°22'N 01°11'W	327°2' * 3240.0 **	319°48' 3925.2	322°6' 4741.8	334°43' 4069.2	328°1' 4456.8	328°33' 5314.2	340°2' 5022.0
NBA 09°04'N 79°39'W	300°9' 7243.8	313°25' 8457.0	307°42' 9238.8	276°57' 7156.8	278°13' 8109.0	261°26' 8227.8	268°40' 6829.2
NAA 44°39'N 67°17'W	311°50' 5761.2	331°33' 6431.4	333°22' 7231.8	314°48' 6361.2	318°13' 6966.0	311°39' 7713.0	309°32' 8440.2
NSS 38°59'N 76°27'W	316°40' 6289.8	333°56' 6919.8	336°16' 7744.8	310°4' 6822.0	315°20' 7477.2	305°52' 8179.8	301°45' 7213.2
WWVL 40°41'N 105°03'W	334°7' 7146.0	358°8' 7221.0	5°1' 7929.0	322°43' 7978.8	336°51' 8394.0	327°54' 9280.2	303°42' 8526.0
NPG 48°12'N 121°55'W	350°9' 7075.2	10°31' 6698.4	16°52' 7297.2	342°13' 8100.0	357°27' 8181.6	359°10' 9118.2	324°48' 9009.0
NPM 21°25'N 158°09'W	33°49' 8337.0	53°29' 6828.0	61°52' 6987.0	46°2' 9439.8	57°57' 7372.8	72°3' 8803.2	109°36' 10150.2

TABLE I. LOCATIONS AND DISTANCES IN NAUTICAL MILES
OF VLF STATIONS AND INDIAN OCEAN PORTS

* Bearing from port to station

** Nautical miles from port to station

VLF STATIONS AND ZONES

PORTS	ZONE	DATE 1963	NBA (+5)			NAA (+5)			NSS (+5)			WWVL (+7)			NPG (+8)			GBR (0)			NPM (+10)			WOODS HOLE		
			SUN	RISE	SET	SUN	RISE	SET	SUN	RISE	SET	SUN	RISE	SET	SUN	RISE	SET	SUN	RISE	SET	SUN	RISE	SET	SUN	RISE	SET
Aden	-3	Aug 3	1050	0250	1523	1050	0250	1523	1050	0250	1523	1050	0250	1523	1050	0250	1523	1050	0250	1523	1050	0250	1523	1050	0250	1523
Bombay	-5½	Aug 13	1051	0009	1501	1051	0009	1501	1051	0009	1501	1051	0009	1501	1051	0009	1501	1051	0009	1501	1051	0009	1501	1051	0009	1501
Ceylon	-5½	Sept 2	1050	0021	1436	1050	0021	1436	1050	0021	1436	1050	0021	1436	1050	0021	1436	1050	0021	1436	1050	0021	1436	1050	0021	1436
Zanzibar	-3	Sept 22	1049	0249	1456	1049	0249	1456	1049	0249	1456	1049	0249	1456	1049	0249	1456	1049	0249	1456	1049	0249	1456	1049	0249	1456
Seychelles	-4	Sept 27	1049	0148	1354	1049	0148	1354	1049	0148	1354	1049	0148	1354	1049	0148	1354	1049	0148	1354	1049	0148	1354	1049	0148	1354
Diego Suarez	-4	Oct 17	1049	0135	1355	1049	0135	1355	1049	0135	1355	1049	0135	1355	1049	0135	1355	1049	0135	1355	1049	0135	1355	1049	0135	1355
Port Luis	-4	Oct 27	1049	0121	1407	1049	0121	1407	1049	0121	1407	1049	0121	1407	1049	0121	1407	1049	0121	1407	1049	0121	1407	1049	0121	1407
Lourenco Marques	-2	Nov 16	1055	0303	1625	1055	0303	1625	1055	0303	1625	1055	0303	1625	1055	0303	1625	1055	0303	1625	1055	0303	1625	1055	0303	1625
Capetown	-2	Nov 21	1057	0244	1644	1057	0244	1644	1057	0244	1644	1057	0244	1644	1057	0244	1644	1057	0244	1644	1057	0244	1644	1057	0244	1644

TABLE II. DIURNAL INFORMATION FOR THE CRUISE OF ATLANTIS II ON THE INDIAN OCEAN, 1963

All times are GMT.

and sunsets. From these two tables, diurnal corrections could be determined and compared with the in-port measurement of the diurnal changes. Figures A-3 through A-9 are examples of overlays that were helpful to determine just when diurnal corrections were needed and over what periods of time. Figure A-10 is a plot of the frequency stability, time, and distance relationship which is useful for quick conversions in correcting the reference oscillator of the VLF system.

In summary, at distances of 5,000 nautical miles from a station, one's position would be in error by about ten nautical miles if diurnal corrections were not applied. It is reasonable to expect that even crude approximations of the diurnal effect will reduce the positioning errors due to this phenomena to less than 1.5 nautical miles. Another factor to be considered is that the night diurnal error is always in the same direction--the indicated range from the transmitting station is increased. There are several semi-automatic systems that may be employed to make the compensation, but these methods vary with the needs of the operators and will not be developed here.

The information above is not applicable to short-range reception of the VLF transmissions. At distances under 1,000 nautical miles, ground and sky wave interference often is experienced at night but can be resolved by an alert operator. In the immediate vicinity of a transmitter (ground wave only), there is no correction to be made to the received signals.

ADEN AUGUST 3, 1963, GMT

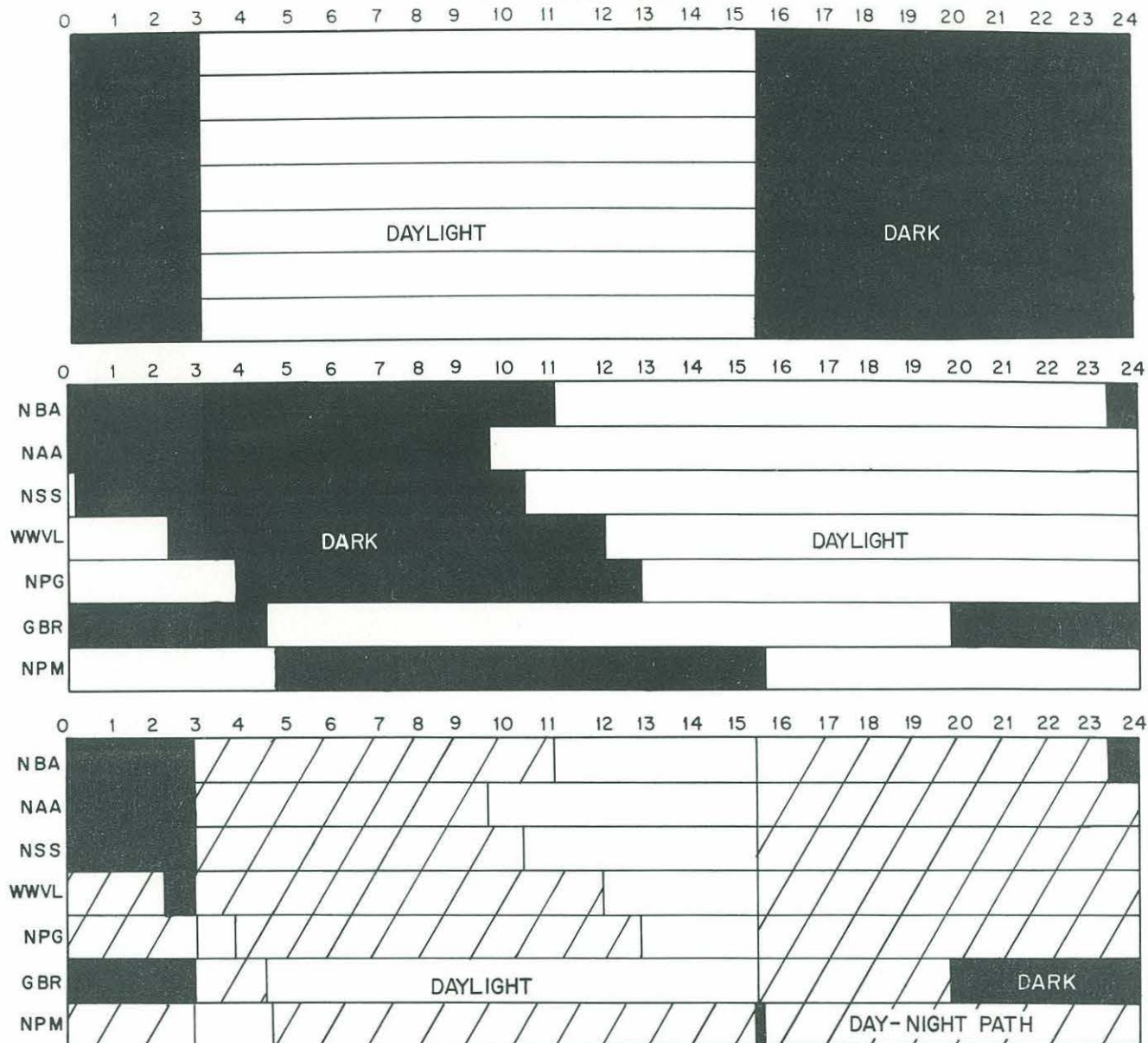


Figure A3 Diurnal overlay for Aden, August 3, 1963.

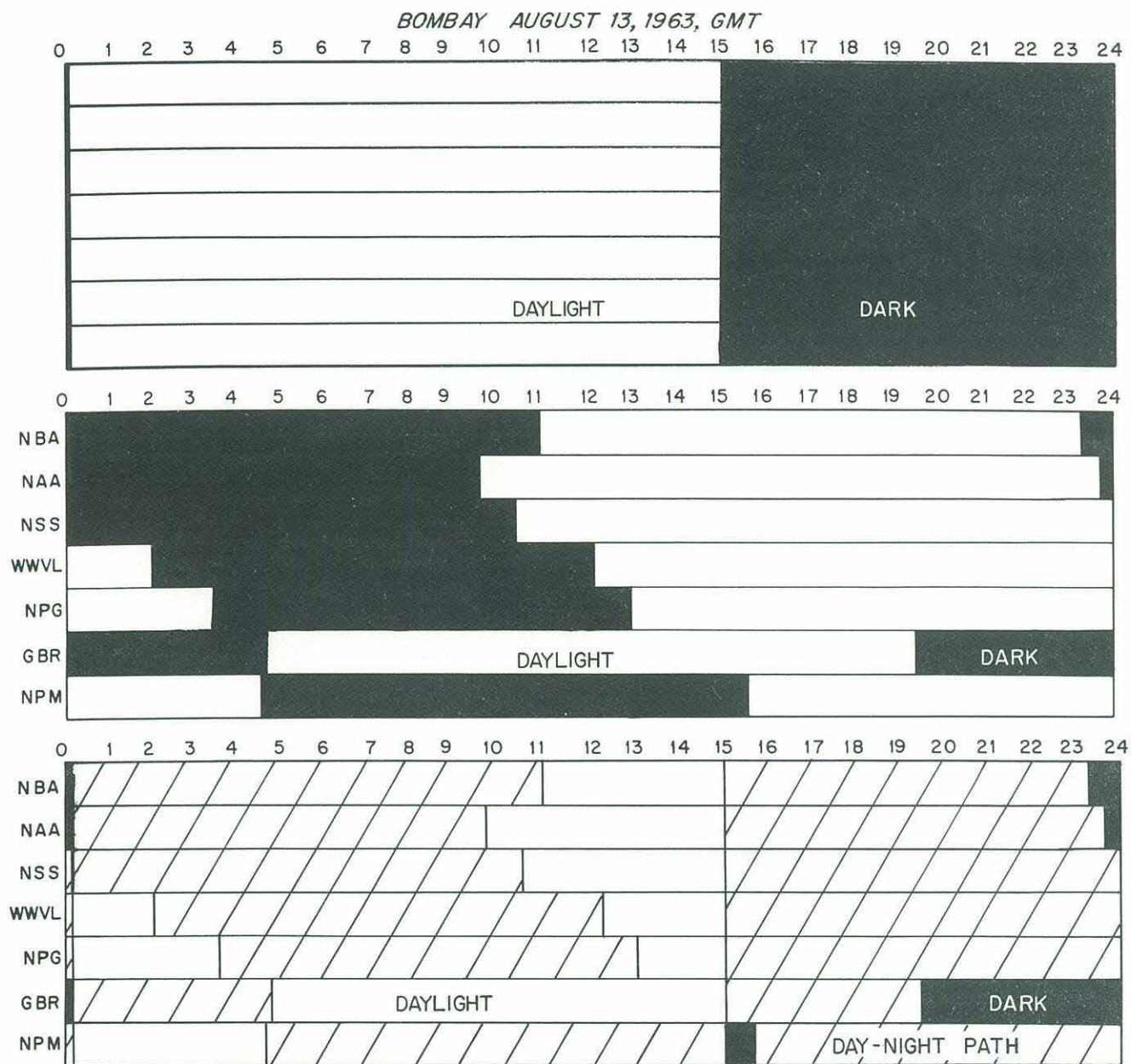


Figure A4 Diurnal overlay for Bombay, August 13, 1963.

CEYLON, SEPTEMBER 2, 1963 GMT

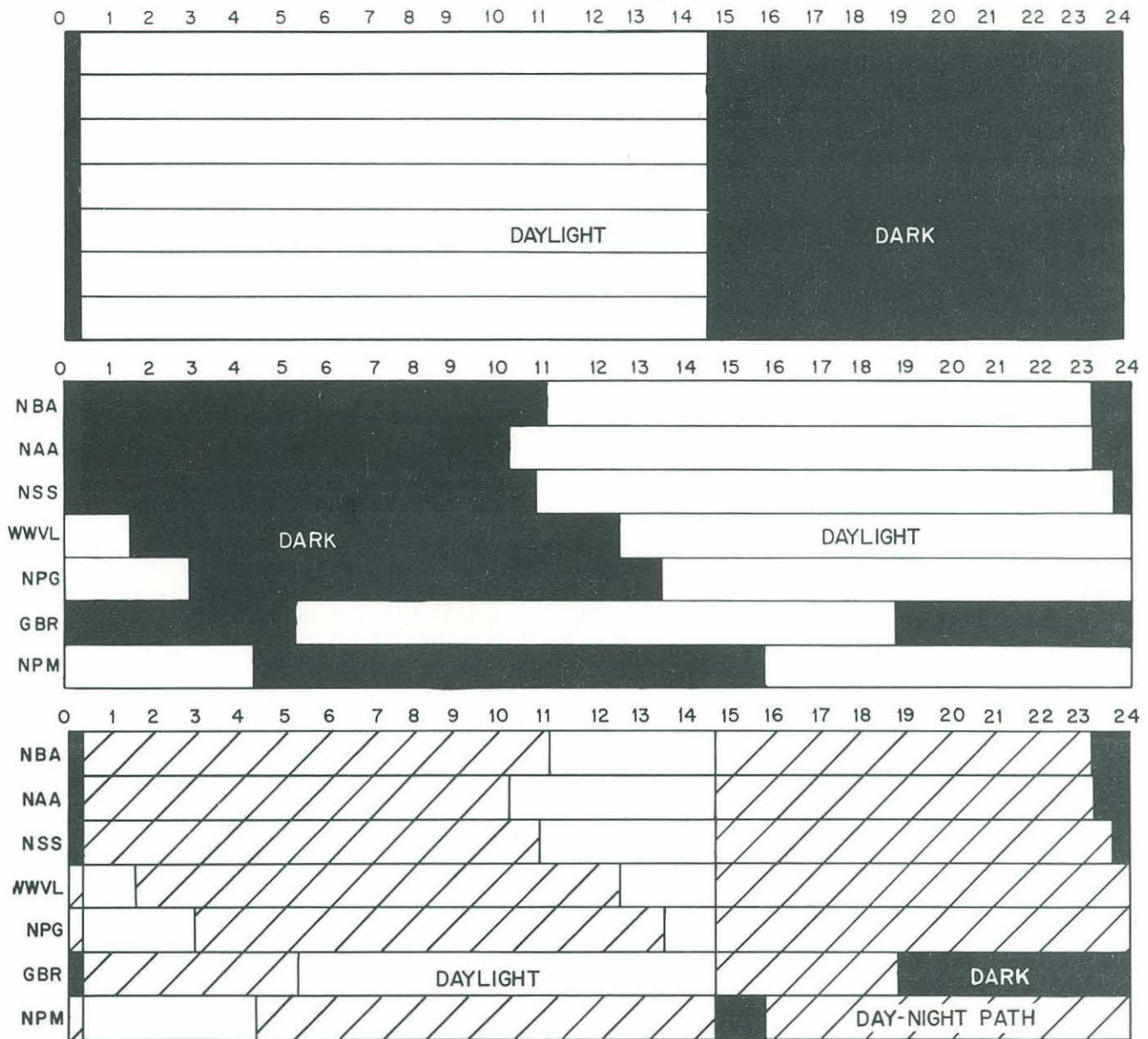


Figure A5 Diurnal overlay for Ceylon, September 2, 1963.

ZANZIBAR, SEPTEMBER 22, 1963, GMT

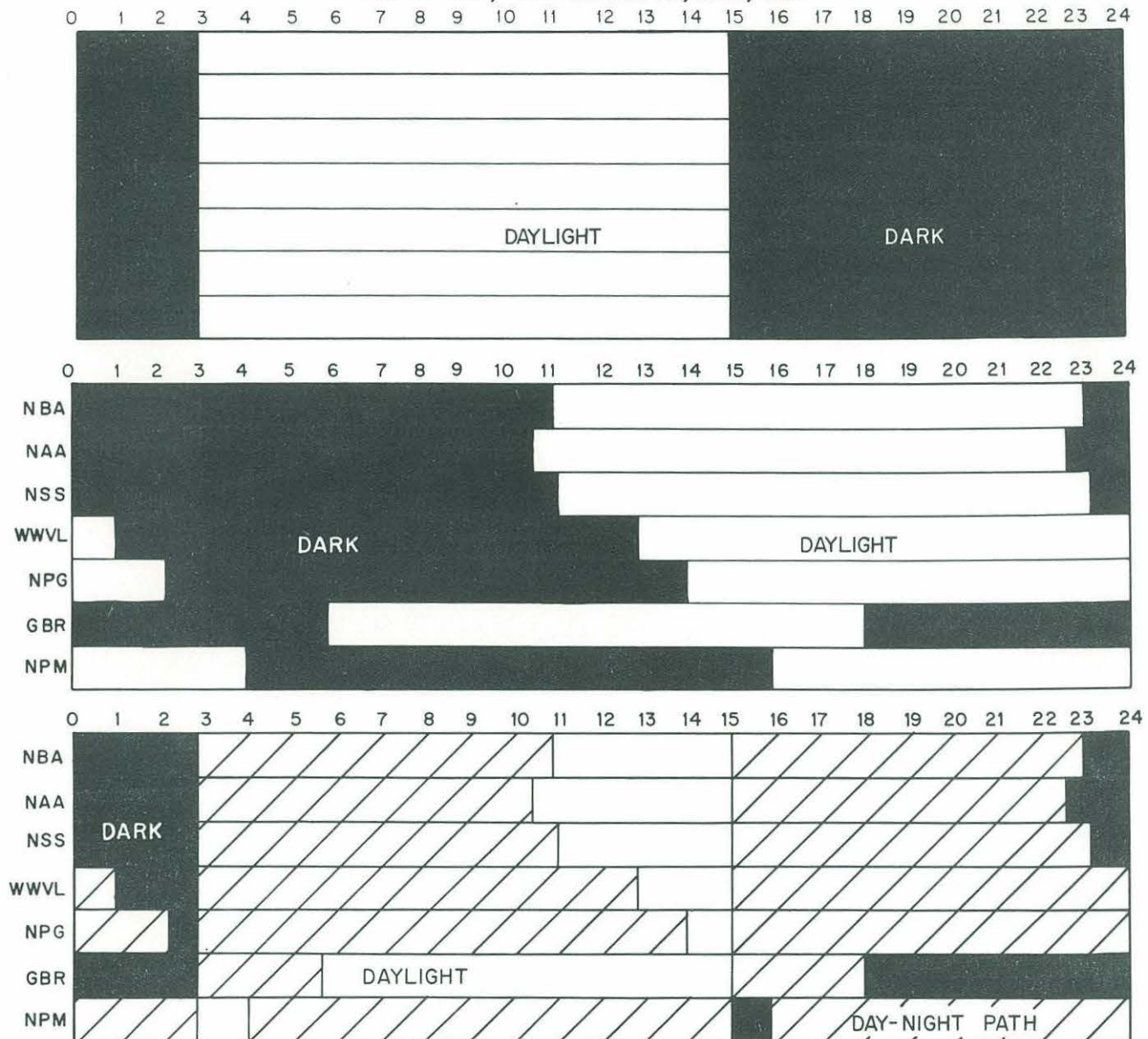


Figure A6 Diurnal overlay for Zanzibar, September 22, 1963.

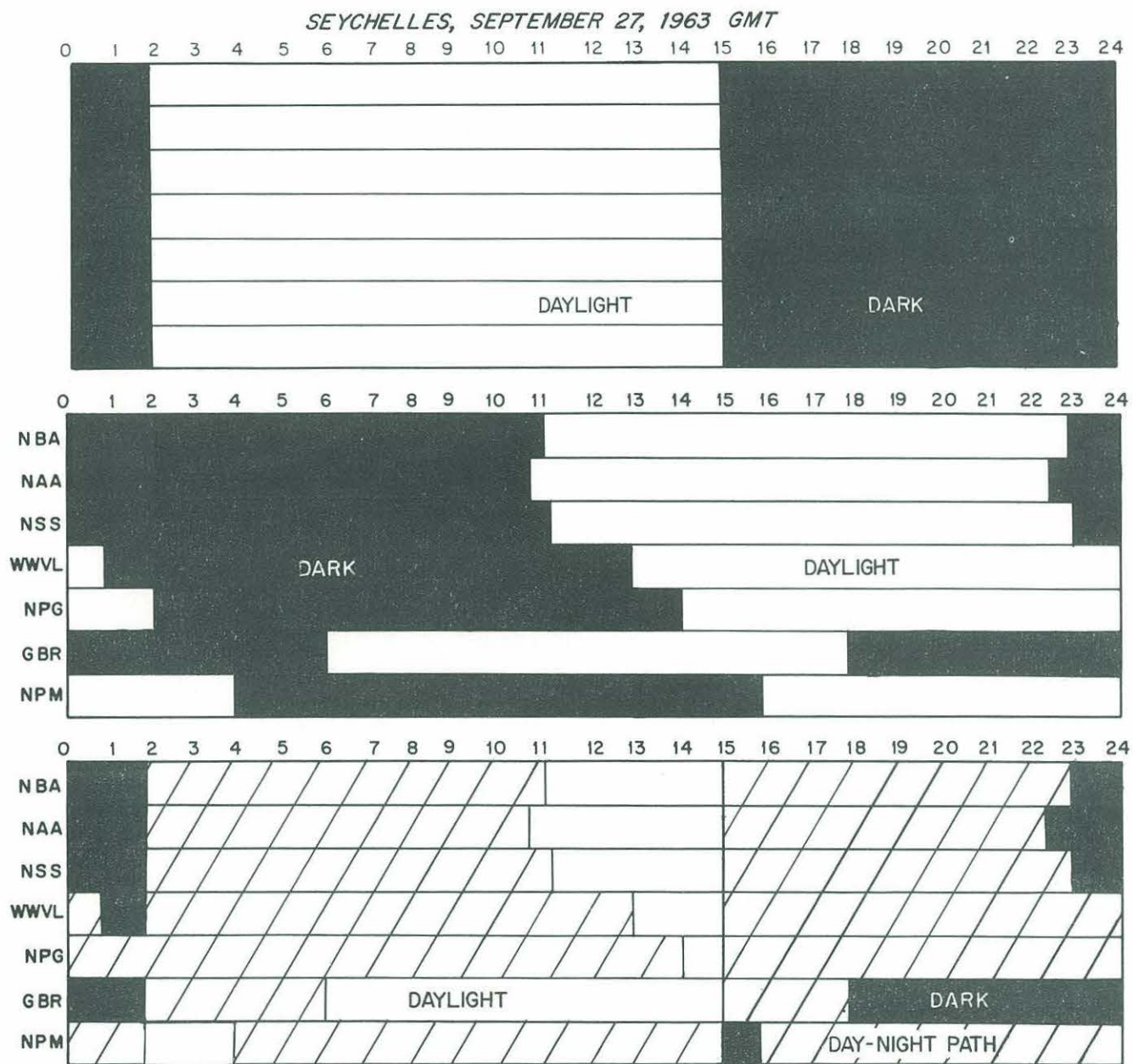


Figure A7 Diurnal overlay for Seychelles, September 27, 1963.

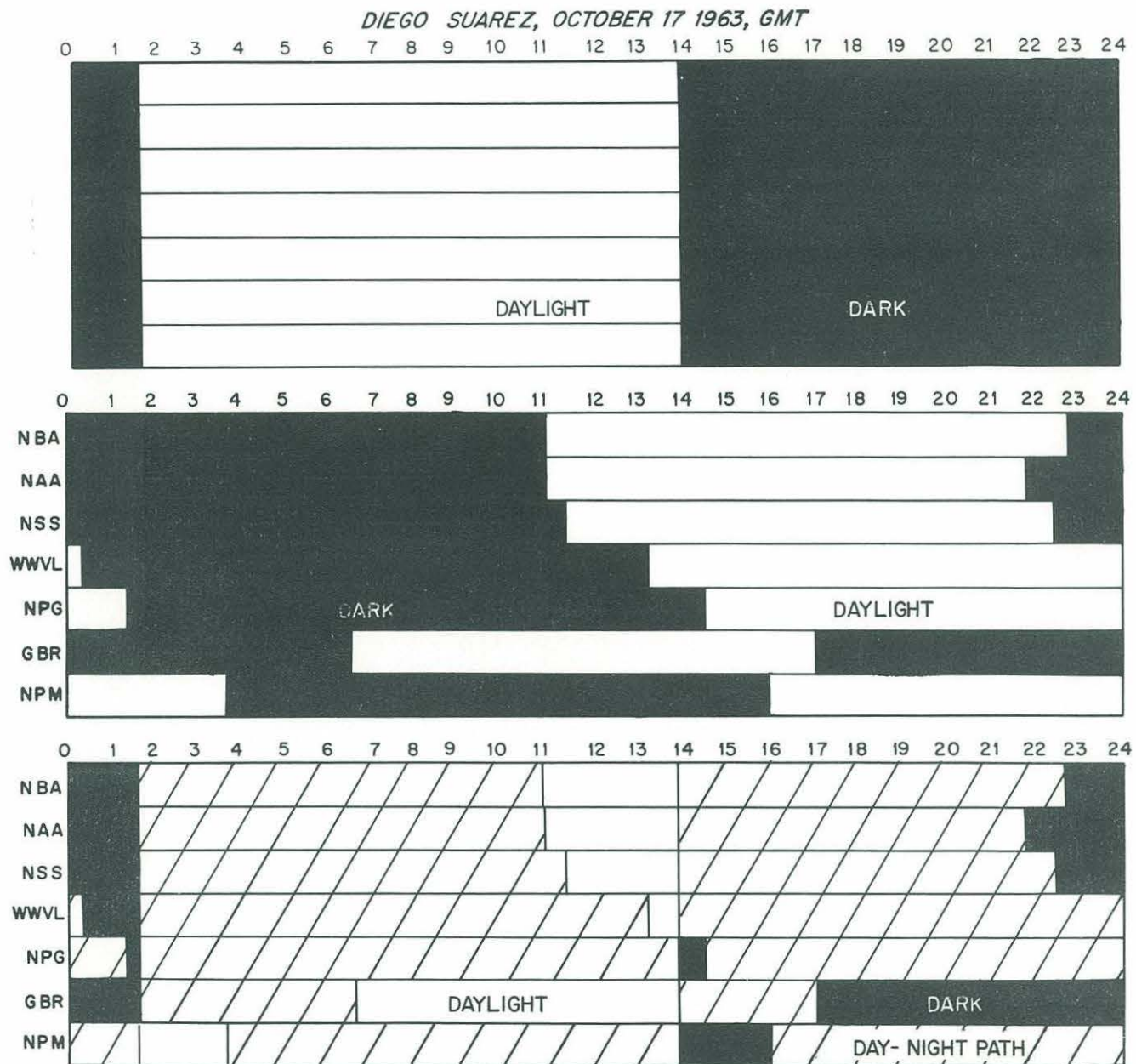


Figure A8 Diurnal overlay for Diego Suarez, October 17, 1963.

MAURITIUS, OCTOBER 27, 1963, GMT

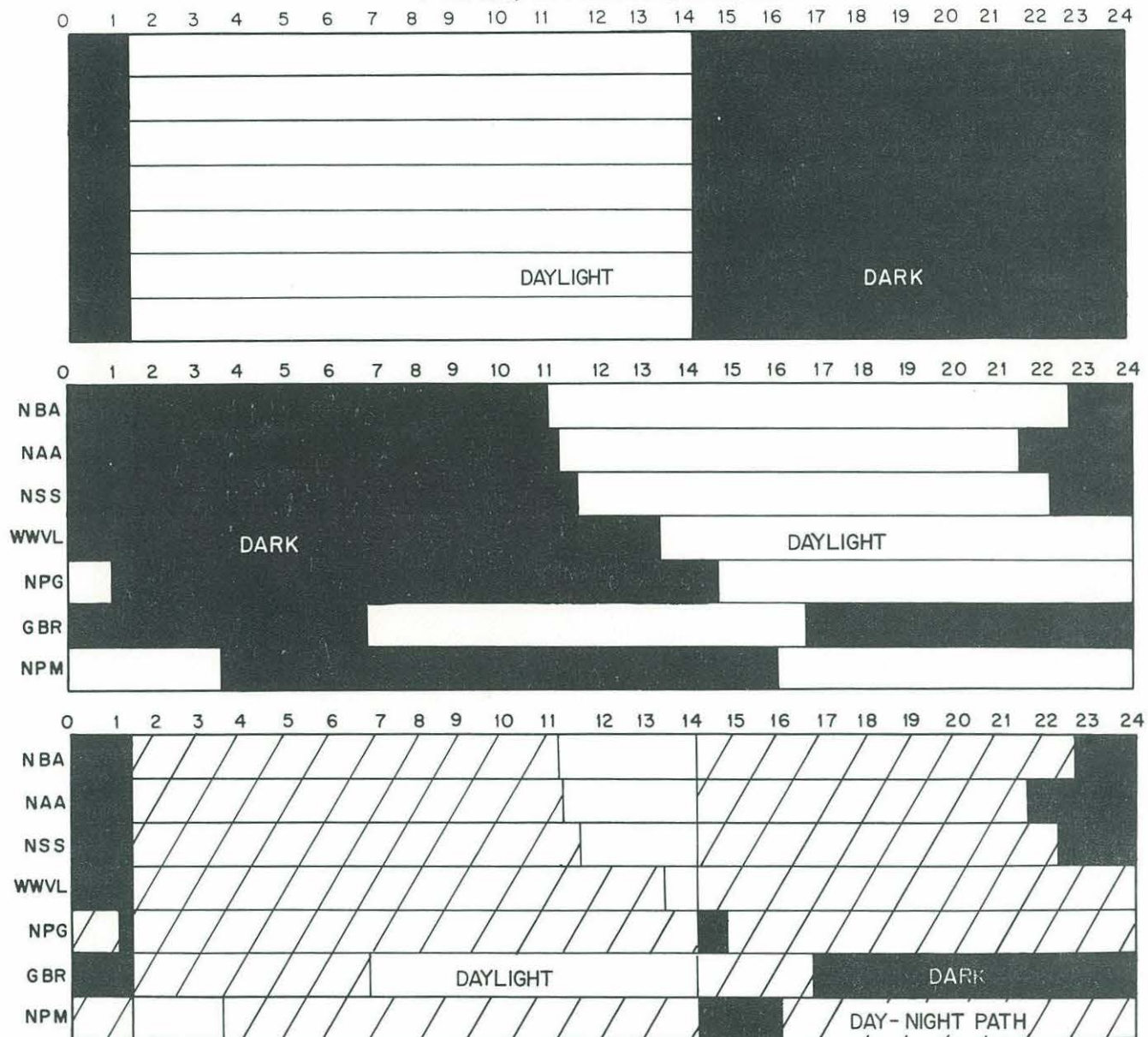


Figure A9 Diurnal overlay for Mauritius, October 27, 1963.

LOURENCO MARQUES, NOVEMBER 16, 1963, GMT

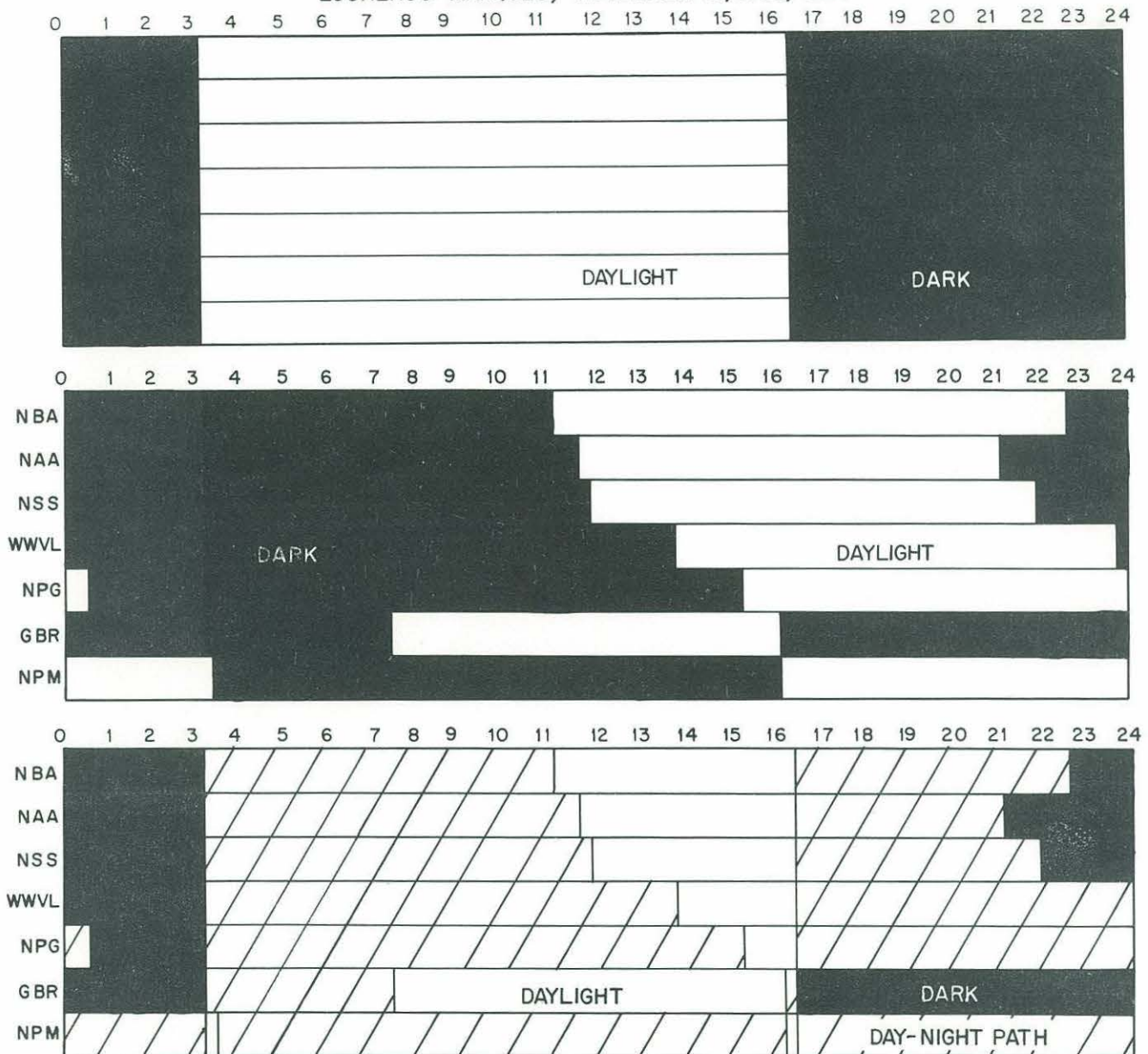


Figure A10 Diurnal overlay for Lourenco Marques, November 16, 1963.

CAPETOWN, NOVEMBER 21, 1963, GMT

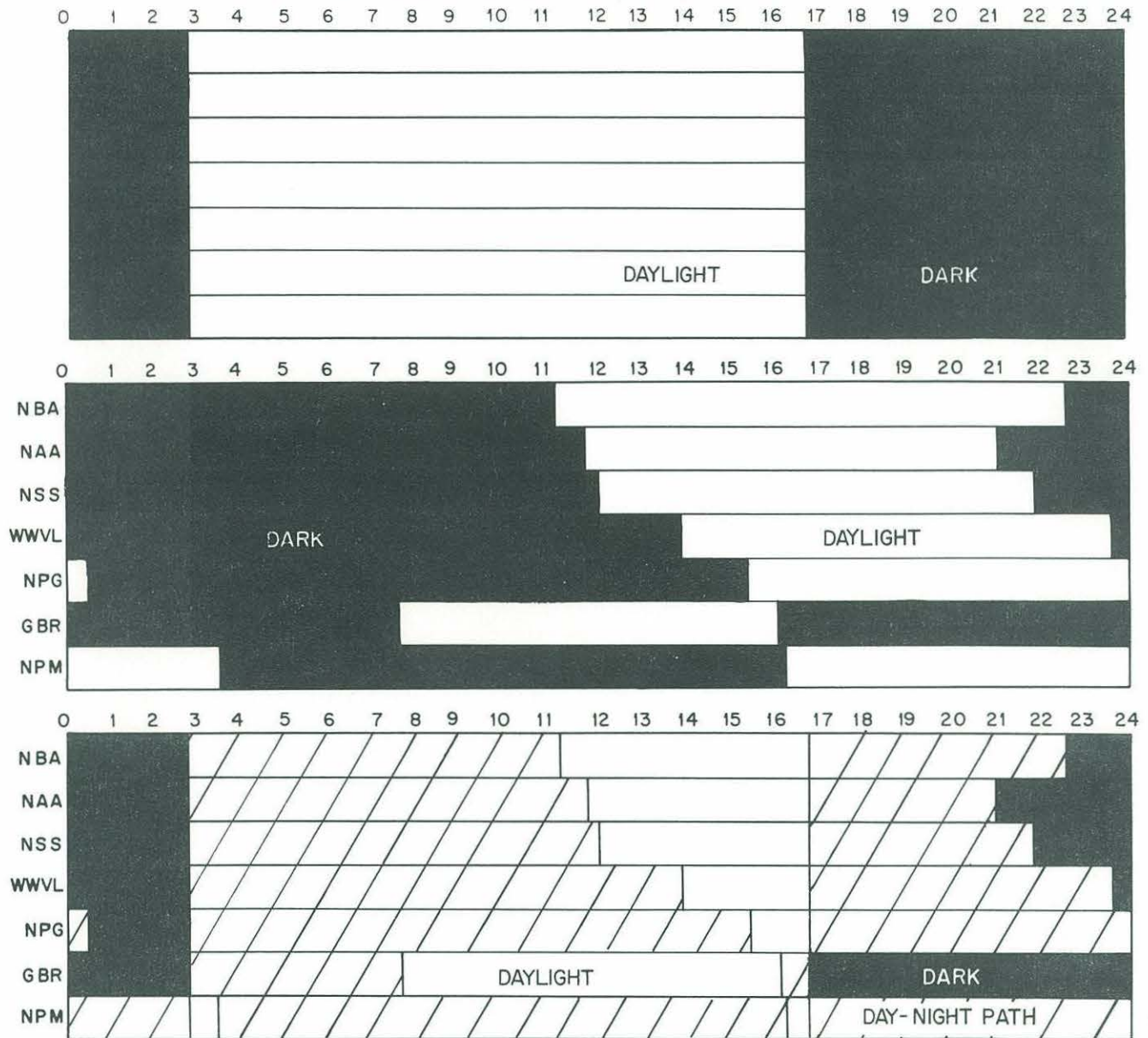


Figure A11 Diurnal overlay for Capetown, November 21, 1963.

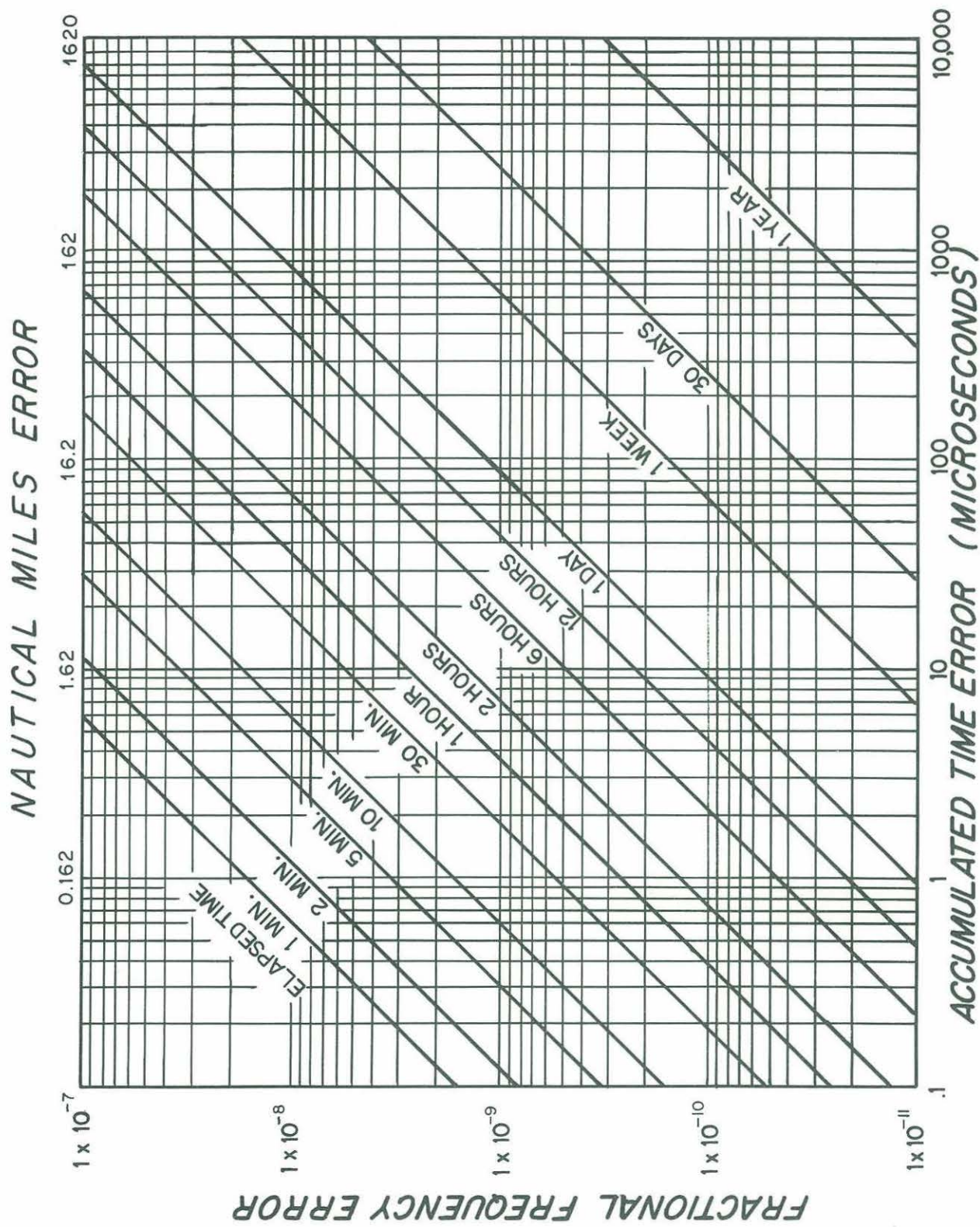


Figure A12 TIME, FREQUENCY, AND NAUTICAL MILES RELATIONSHIP FOR VLF NAVIGATION.

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Woods Hole Oceanographic Institution Reference No. 66-61	1. Oceanographic Navigation 2. Very Low Frequency 3. ATLANTIS II 4. Stanbrough
<p>EXPERIMENTAL VLF RELATIVE NAVIGATION ON R/V ATLANTIS II, CRUISE 15 by J. H. Stanbrough, Jr. 38 pp. November 1966. Contract N0HR-3351(00) NR083-501 and NSF Grant 821.</p> <p>An experimental long-range relative navigation system was employed on the Research Vessel ATLANTIS II of the Woods Hole Oceanographic Institution during Cruise 8 to the Indian Ocean in 1963 and Cruise 15 which circumnavigated the globe in 1965.</p> <p>The very low frequencies (VLF) transmitted by stations having stabilized carriers (a few parts in 1011) can be received throughout the world. Navigational information is obtained from the comparison of the received signals of two or more stations with a precision oscillator which serves as a reference. Geographical changes result in phase changes which may be computed to longitude and latitude if the starting point is known; thus, the system is relative.</p> <p>Reference points could be supplied to the VLF system from a satellite radio navigator that was loaned by the U.S. Navy for this cruise. Best positioning agreed to within 1-3 nautical miles from best ship's position under favorable conditions. The VLF equipment also was able to provide (1) a measure of ship's drift on station, (2) precise time and frequencies, and (3) a means for calibrating the ship's EM log at sea.</p>	<p>I. Stanbrough, J. H. Jr. II. N0HR 3351(00) NR083-501 NSF Grant 821</p> <p>This card is UNCLASSIFIED</p>

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13. ABSTRACT <p>An experimental long-range relative navigation system was employed on the Research Vessel ATLANTIS II of the Woods Hole Oceanographic Institution during Cruise 8 to the Indian Ocean in 1963 and Cruise 15 which circumnavigated the globe in 1965.</p> <p>The very low frequencies (VLF) transmitted by stations having stabilized carriers (a few parts in 10¹¹) can be received throughout the world. Navigational information is obtained from the comparison of the received signals of two or more stations with a precision oscillator which serves as a reference. Geographical changes result in phase changes which may be computed to longitude and latitude if the starting point is known; thus, the system is relative.</p> <p>Reference points could be supplied to the VLF system from a satellite radio navigator that was loaned by the U.S. Navy for this cruise. Best positioning agreed to within 1-3 nautical miles from best ship's position under favorable conditions. The VLF equipment also was able to provide (1) a measure of ship's drift on station, (2) precise time and frequencies, and (3) a means for calibrating the ship's EM log at sea.</p>			

14.	KEY WORDS	LINK A		LINK B		LINK C	
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